

An overview of the computational effort to analyze forebody tangential slot blowing is presented. Tangential slot blowing generates side force and yawing moment which may be used to control an aircraft flying at high angle of attack. Two different geometries are used in the analysis--the High Alpha Research Vehicle, which is a highly instrumented F/A-18, and a generic chined forebody. Computations using the isolated F/A-18 forebody are obtained at full-scale wind tunnel test conditions for direct comparison with available experimental data. Additional non-time-accurate solutions using the isolated forebody are used to predict the effect of slot blowing at transonic flight conditions. The effects of over- and under-blowing on force and moment production are analyzed. Time-accurate solutions using the isolated forebody are obtained to study the force onset time lag of tangential slot blowing. The effect of blowing on the burst point location are analyzed by obtaining computations using the aircraft geometry, which includes the wing, empennage, and faired-over inlets. The effect of blowing on the aerodynamic loads on the vertical tails are analyzed using time-accurate computations. Comparison with available experimental data from full-scale wind tunnel and sub-scale wind tunnel tests are made. Computations using the generic chined forebody are obtained at experimental wind tunnel conditions, and the results compared with available experimental data. The effect of jet parameters and slot location are studied. This computational analysis compliments the experimental results and provides a detailed understanding of the effects of tangential slot blowing on the flow field about simple and complex geometries.

COMPUTATIONAL ANALYSIS OF FOREBODY TANGENTIAL SLOT BLOWING

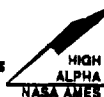
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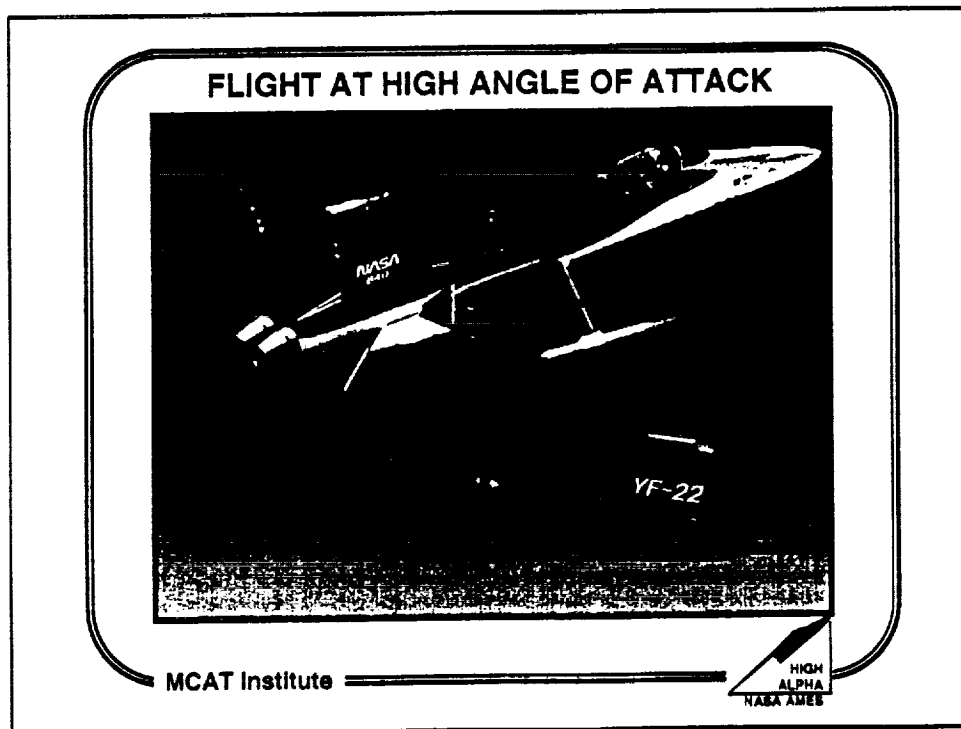
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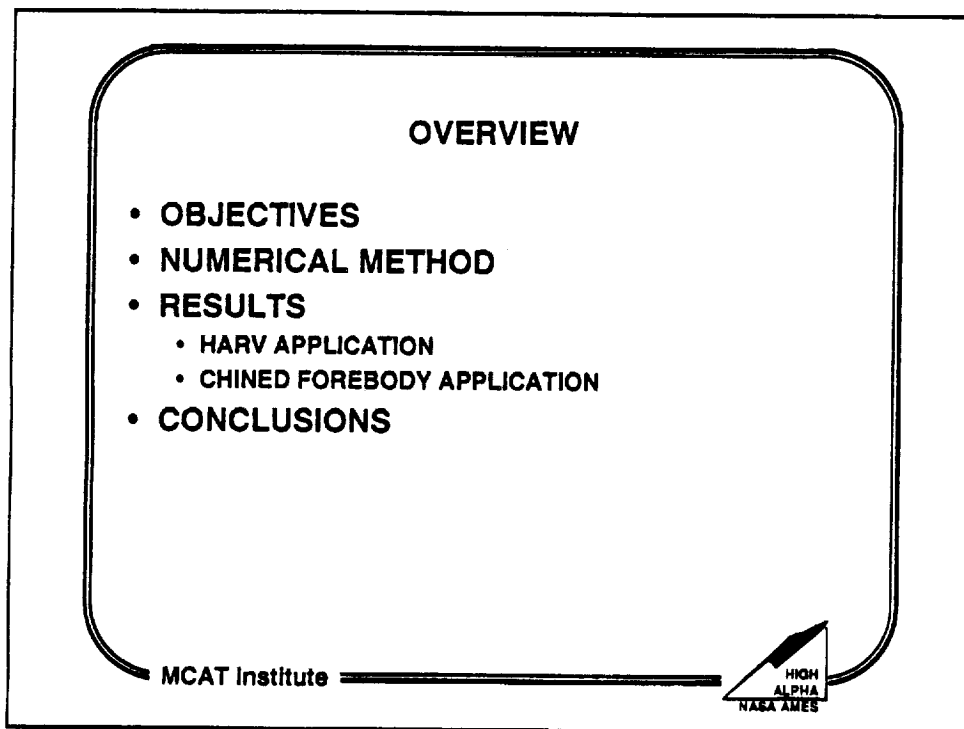
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Aircraft flying at high incidence may experience a large, unintended side force and yawing moment which can lead to departure of the aircraft from the desired flight path. Forebody tangential slot blowing can be used to provide the pilot with a means to control the side force and yawing moment and use them to control the aircraft. The numerical investigation focuses on the implementation of forebody tangential slot blowing on the NASA High Alpha Research Vehicle (HARV). The HARV is a highly instrumented F/A-18 used in flight tests to obtain a database on the behavior of the flow field about aircraft flying at high angles of attack. Since future aircraft designs, such as the YF-22, differs from the F/A-18 in the use of a chined forebody instead of a smooth, rounded forebody, forebody tangential slot blowing is also applied to a generic chined forebody to investigate the effectiveness of such a combination.



An overview of the presentation is shown in this slide. The objectives of the numerical study will be outlined. The numerical method used to solve the governing equations is briefly discussed, including the flow solver used, the grid system employed, and the boundary conditions applied. The results are presented in two parts. The first part covers the effectiveness of forebody tangential slot blowing on the HARV geometry, using both isolated forebody and wing/body/tail geometries. The second part presents results of applying forebody tangential slot blowing on an isolated chined forebody. Finally, conclusions drawn from the results obtained during from this investigation is presented.



The investigation involving the HARV configuration is divided into four parts. A solution using the isolated HARV forebody is obtained at full-scale wind tunnel test conditions and compared with experimental data to determine the accuracy of the numerical method and the ability of the method to resolve the surface pressure coefficients. Solutions using a more complete geometric representation of the HARV, including wing, deflected leading-edge flap, empennage, and faired-over engine inlet, show the effect of blowing on the flow field about the aircraft. These solutions provide clues about how the side force and yawing moment are generated. Time-accurate solutions using the aircraft geometry provide data on the changes in the aerodynamic loads on the vertical tails due to blowing. This can have an effect on tail buffet. Finally, the effect of freestream Mach number on blowing over the isolated HARV forebody is investigated. The use of the isolated forebody allows for a number of solutions to be made, so that a range of Mach numbers and jet mass flow rates can be investigated. The analysis of blowing on the chined forebody also includes comparison of computed results with experimental data, along with an investigation of the effect of jet parameters and slot location on force and moment generation at various angles of attack.

OBJECTIVES

- **DETERMINE EFFECTIVENESS OF FOREBODY TANGENTIAL SLOT BLOWING ON HARV CONFIGURATION**
 - DETERMINE ACCURACY OF NUMERICAL METHOD
 - DETERMINE EFFECT OF BLOWING ON FLOW FIELD ABOUT AIRCRAFT
 - DETERMINE EFFECT OF BLOWING ON AERODYNAMIC LOADS ON VERTICAL TAILS
 - DETERMINE EFFECT OF FREESTREAM MACH NUMBER ON BLOWING
- **DETERMINE EFFECTIVENESS OF BLOWING ON CHINED FOREBODY**
 - DETERMINE ACCURACY OF NUMERICAL METHOD
 - DETERMINE EFFECT OF JET AND SLOT PARAMETERS

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To simplify the process of generating grids about a complex geometry such as the HARV, the overset grid method¹ is used. In this method, the HARV geometry is divided into parts, and separate grids are generated about each part using a hyperbolic grid generator. The grids are then combined and a communication scheme is generated to pass boundary information among overlapping grids. The communication scheme does not require the grid boundaries to match faces.

Since the flow about an aircraft flying at high angle of attack is three-dimensional and separated, solution of the three-dimensional, thin-layer Navier-Stokes equations is required to accurately model the flow. The flow solver used to solve the Navier-Stokes equations is F3D.² F3D uses approximate factorization and partial flux splitting to obtain upwind differencing in the streamwise direction and central differencing in the other two directions. F3D is second-order accurate in space, and can be first- or second-order accurate in time. The time-accurate computations use first-order time accuracy. The solutions are obtained assuming fully turbulent flow. For closure, the Baldwin-Lomax algebraic turbulence model³ is used. In the fuselage and forebody grids, the Degani-Schiff modifications⁴ to the Baldwin-Lomax model is implemented.

NUMERICAL METHOD

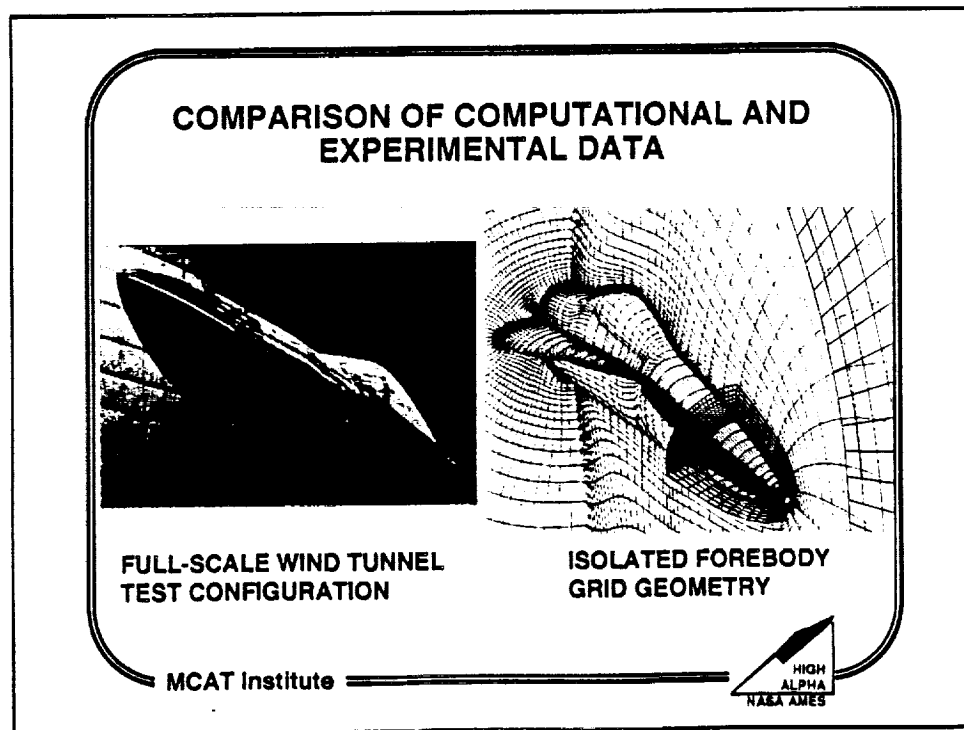
- **OVERSET GRIDS**
 - GRIDS GENERATED USING HYPERBOLIC METHODS
 - SIX GRIDS MODEL THE FOREBODY GEOMETRY
- **F3D ALGORITHM**
 - SOLVES THIN-LAYER NAVIER-STOKES EQUATIONS
 - APPROXIMATELY FACTORED, PARTIALLY-FLUX SPLIT
 - UPWIND DIFFERENCING STREAMWISE, CENTRAL DIFFERENCING OTHER TWO DIRECTIONS
 - FULLY TURBULENT COMPUTATIONS
 - BALDWIN-LOMAX TURBULENCE MODEL WITH DEGANI-SCHIFF MODIFICATIONS

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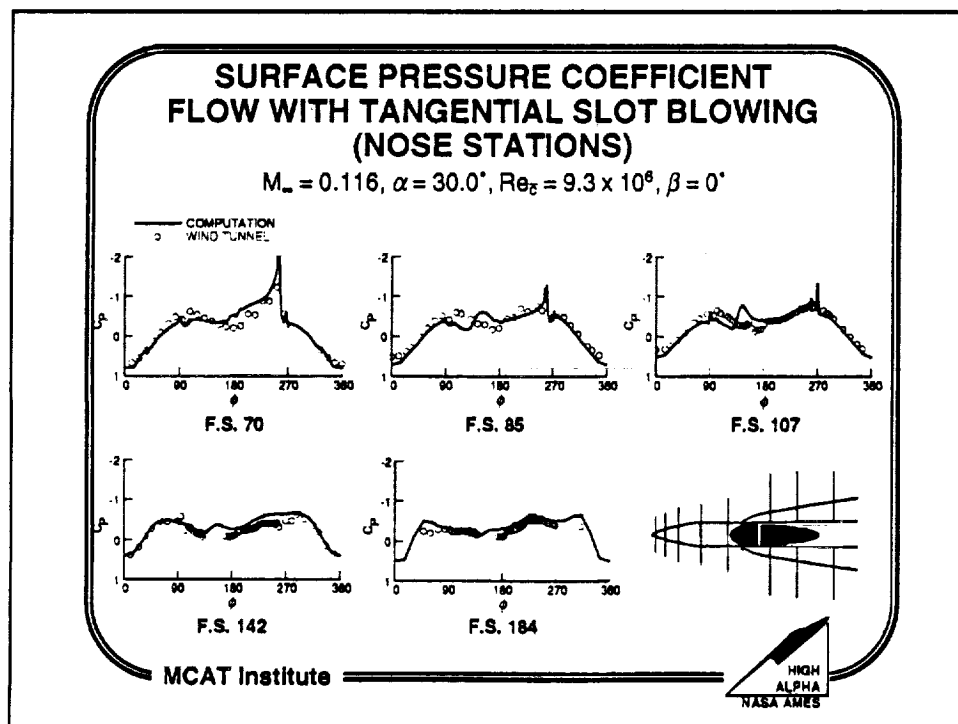


Full-scale wind tunnel experiments were carried out in the NASA Ames 80 by 120 ft. wind tunnel using an F/A-18 model.⁵ The model was fitted with a forebody tangential slot blowing system. The system consisted of a 48 in. slot, beginning 3 in. from the nose. The slot was divided into six 8 in. sections. Each section was connected to a valve, which in turn led to a plenum. Thus, the active slot length can be controlled. Blowing occurred on the port side. A dummy slot was located on the starboard side to maintain symmetry in the model.

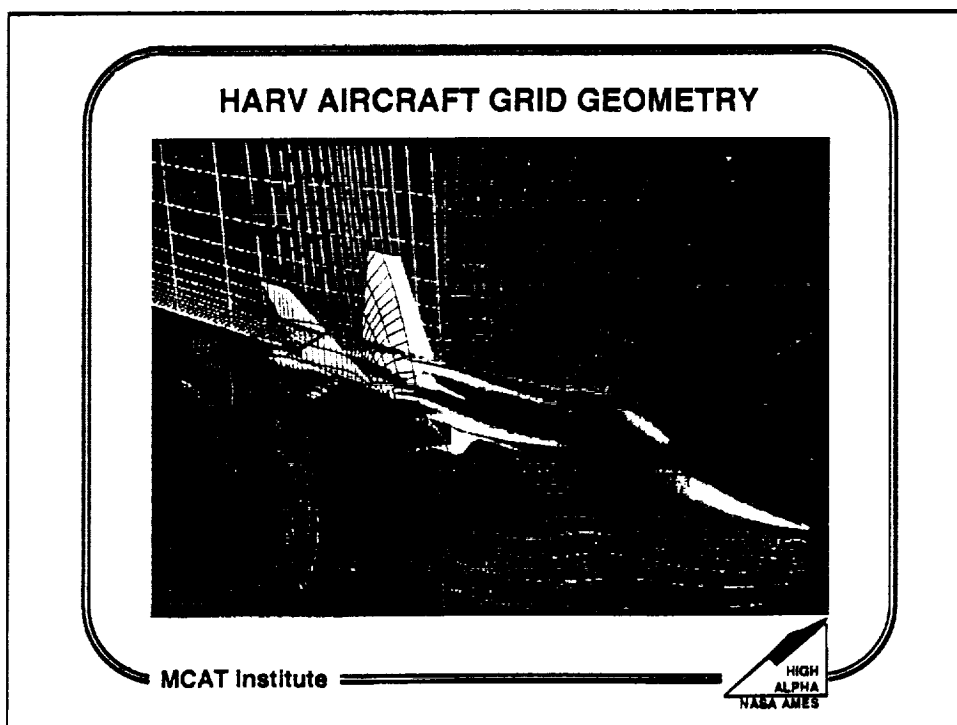
The computational grid system modeled this slot geometry, including the backward-facing step of the slot itself. The active slot length is controlled through the use of boundary conditions that model the jet parameters. A solution is obtained using the isolated forebody geometry at wind tunnel test conditions.⁶ The results are then compared with the experimental data to determine the accuracy of the numerical method, especially in the jet region.



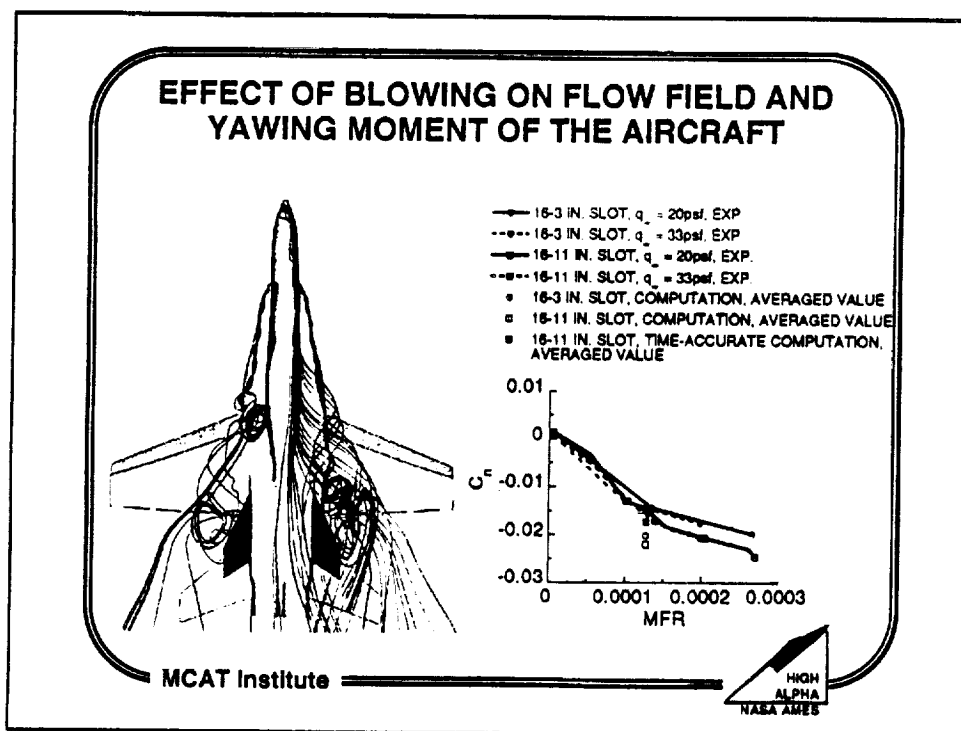
The computed surface pressure coefficient is compared with full-scale wind tunnel test data at the five pressure stations located on the forebody barrel. The computed results compare quite well with the experimental data. The computed results resolve the suction peak due to the attached jet quite accurately in the first two pressure ring locations. There is a suction peak associated with the separation of the jet in the computational result, located near $\phi = 200^\circ$, which does not occur in the experimental data. This may be due to the use of the Baldwin-Lomax turbulence model in the attached jet region. At the aft two pressure rings, the asymmetry in the pressure distribution is resolved, with the blowing-side surface pressure slightly lower than the non-blowing-side surface pressure. This contributes to the side force and yawing moment obtained from blowing. These results provides confidence in the numerical method to accurately predict the effects of forebody tangential slot blowing on the flow field about the F/A-18.



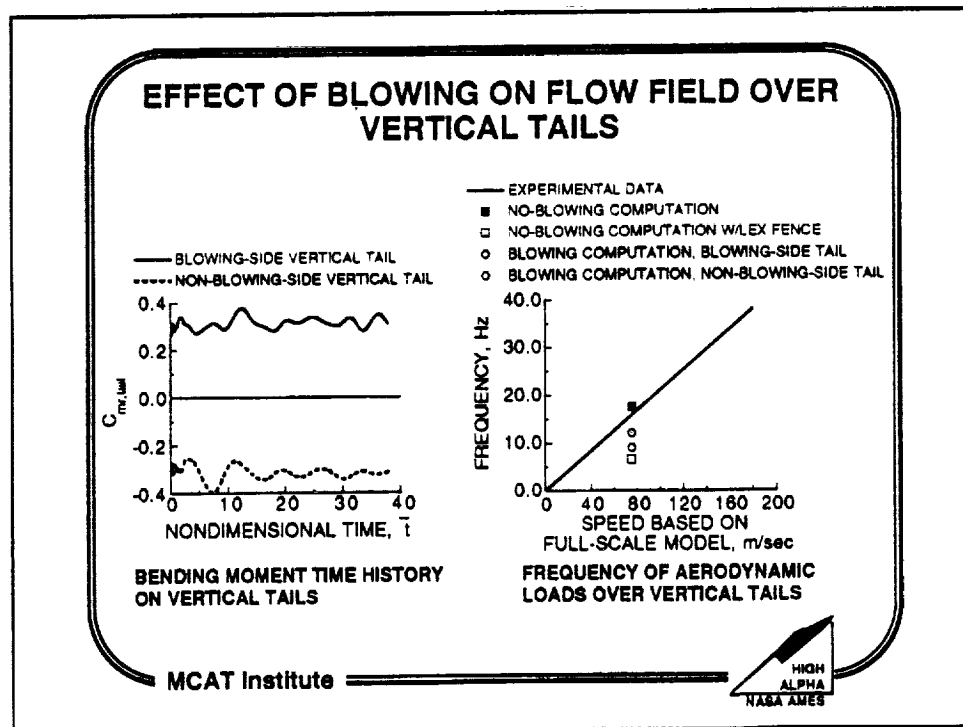
Since blowing has an effect on the entire flow field about an aircraft flying at high angle of attack, solutions are obtained using the aircraft geometry model at a typical flight condition.⁷ The solutions show the effect of blowing on the flow field and the ability of the blowing system to operate at a flight condition. The grid system consists of 22 grids, totalling 1.8 million grid points. The computational grid model contains the major features of the HARV, including the wing, deflected leading-edge flap, and vertical and horizontal tails. Simplifications are introduced to facilitate the modeling. The engine inlets are faired-over and the boundary layer diverter vent is highly simplified. However, these simplifications should have minimal impact on the major flow characteristics.



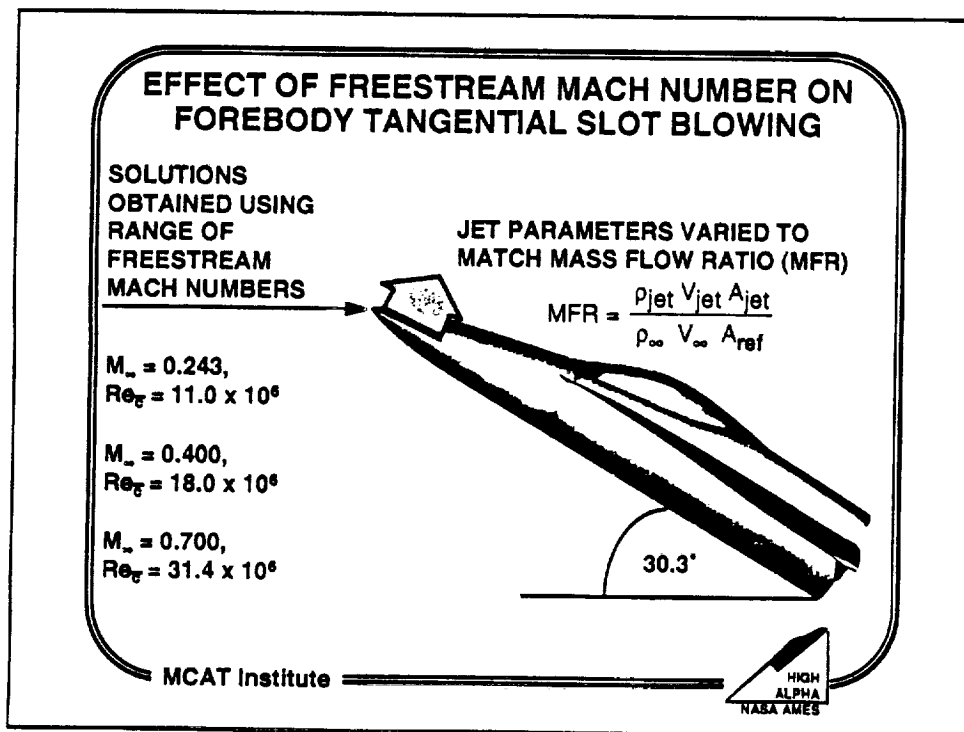
The effect of forebody tangential slot blowing is not limited to the flow field about the nose. The most noticeable effect on the flow field about the aircraft is the asymmetric LEX vortex burst caused by blowing. The blowing-side LEX vortex bursts sooner than the non-blowing-side LEX vortex, as shown in the above figure. This has been confirmed by flow visualization taken in the full-scale wind tunnel tests. However, the computed burst point position of both LEX vortices are aft of the burst points observed in the experiment. This is due to using a coarse grid system. The blowing-side LEX vortex becomes stronger than the non-blowing-side LEX vortex, which leads to the asymmetric burst points. This difference in vortex strength also creates a side force and yawing moment in the direction of the blowing side. The yawing moment obtained from the computations compare quite well with the experimental data from the full-scale wind tunnel test. Since the flow aft of the vortex burst is unsteady, the averaged time-accurate yawing moment agrees better with the experimental values than does the averaged steady-state yawing moments. However, the averaged steady-state yawing moments do provide a good approximation without the computational expense of the time-accurate solution.



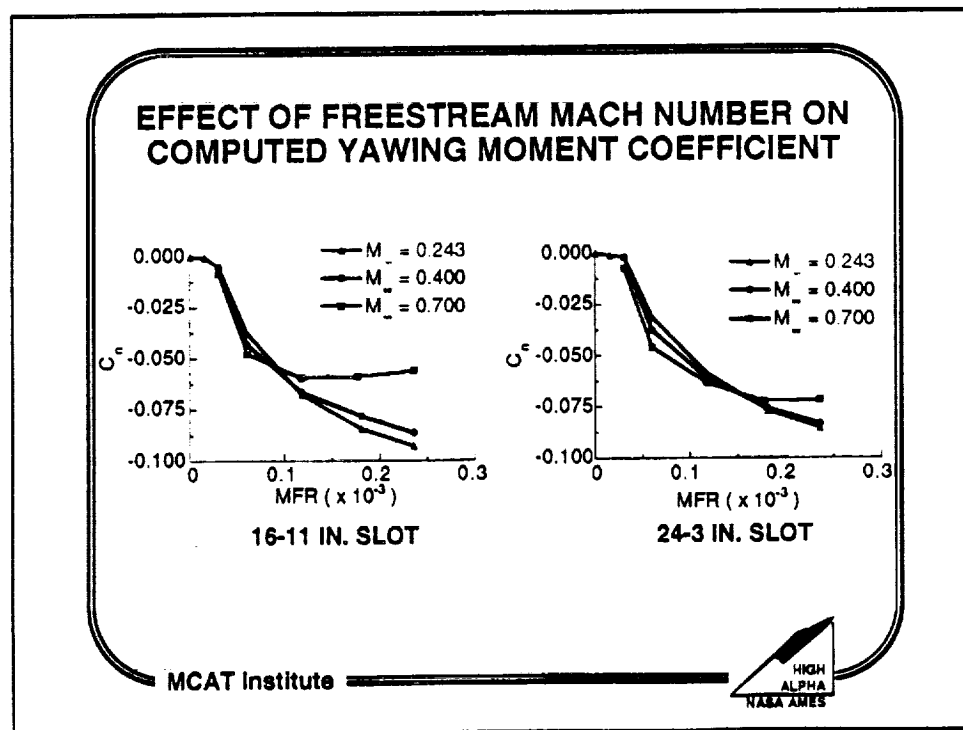
Time-accurate computations show that blowing has an effect on the frequency content of the aerodynamic loads on the vertical tails.⁷ The computations were done using a rigid tail (i.e., no movement of the vertical tails due to the loads were simulated). The computed bending moment on the vertical tails show an oscillatory load on the tails. A Fast Fourier Transform analysis of the bending moment time history shows that the dominant frequency of aerodynamic loads on the vertical tails are 9 Hz for the blowing-side tail, and 12 Hz for the non-blowing-side vertical tail. These frequencies are slightly lower than that obtained in no-blowing computations and experiments. This indicates that blowing has an effect on the load frequencies, and therefore the tail buffet phenomenon.



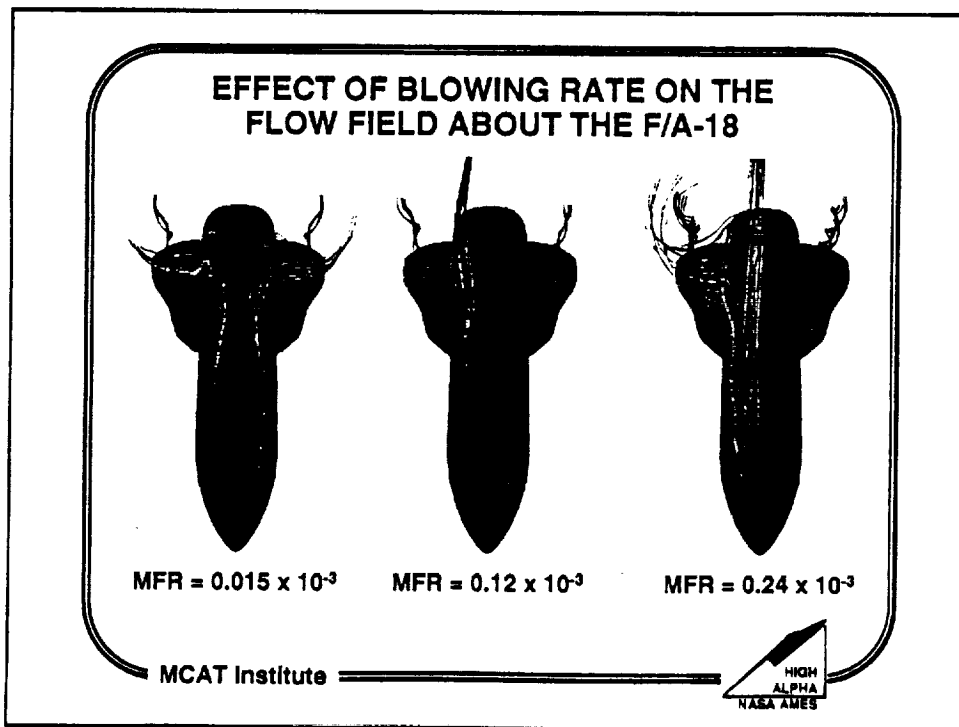
High performance fighter aircraft can maneuver in the high-angle-of-attack regime at transonic speeds. In order to determine the effect the freestream Mach number has on blowing, the problem is investigated numerically.⁸ To best utilize available computational resources, the isolated forebody geometry is used in this part of the study. The smaller grid system requires less computer time, meaning more solutions can be obtained, allowing for a study at a variety of freestream velocities and jet conditions. Three freestream Mach number values are studied. At each freestream Mach number, different jet mass flow rates are used. The jet mass flow rate is determined by keeping the mass flow ratio (MFR) constant across the Mach number spectrum. The MFR is defined as the ratio of the jet mass flow rate and a reference mass flow rate based on freestream density, freestream velocity, and wing area.



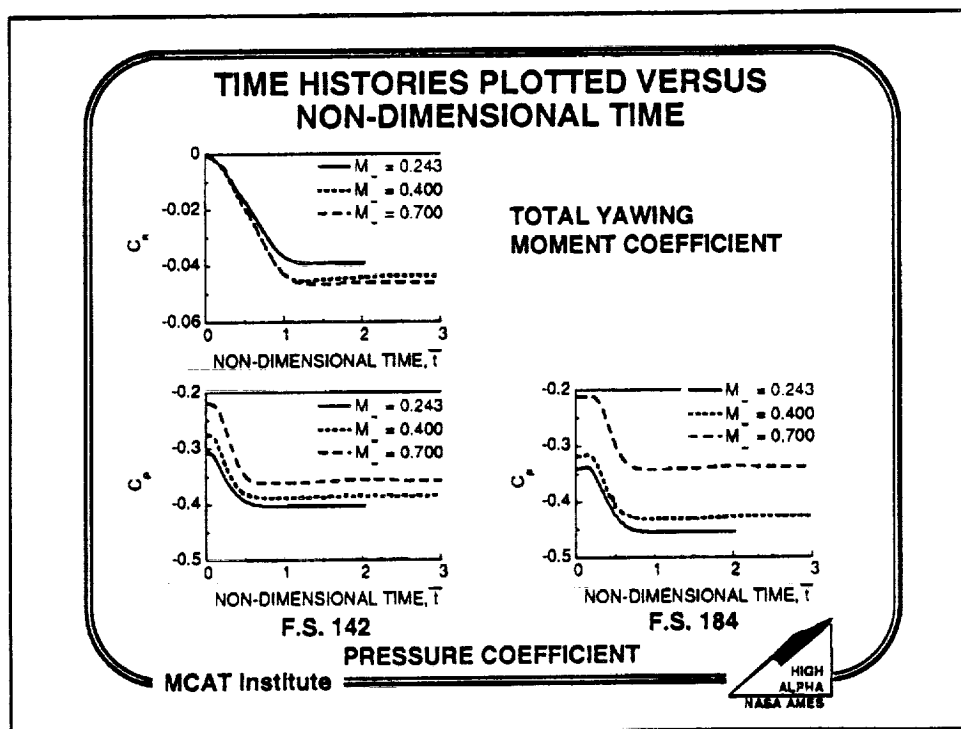
In order to determine the effectiveness of tangential slot blowing at higher freestream Mach numbers, computations are obtained using the F/A-18 isolated forebody with blowing at subsonic and transonic Mach numbers. At each freestream Mach number, solutions are obtained using a number of mass flow ratios. The correlation with MFR holds fairly well as the blowing rate increases and only breaks down at high blowing rates and high freestream Mach number. At high blowing rates and high freestream Mach number, overblowing occurs. Overblowing is characterized by a leveling off or drop in yawing moment with increasing blowing rates. Analysis of the computational results indicates the jet is underexpanded as it leaves the slot and separates fairly quickly. This early separation reduces the low pressure region caused by the jet and reduces the effect of the jet on the forebody vortices. Both of these effects contribute to a reduction in the yawing moment. This problem may be avoided by increasing the slot area, thereby reducing the total pressure required for a desired jet mass flow rate.



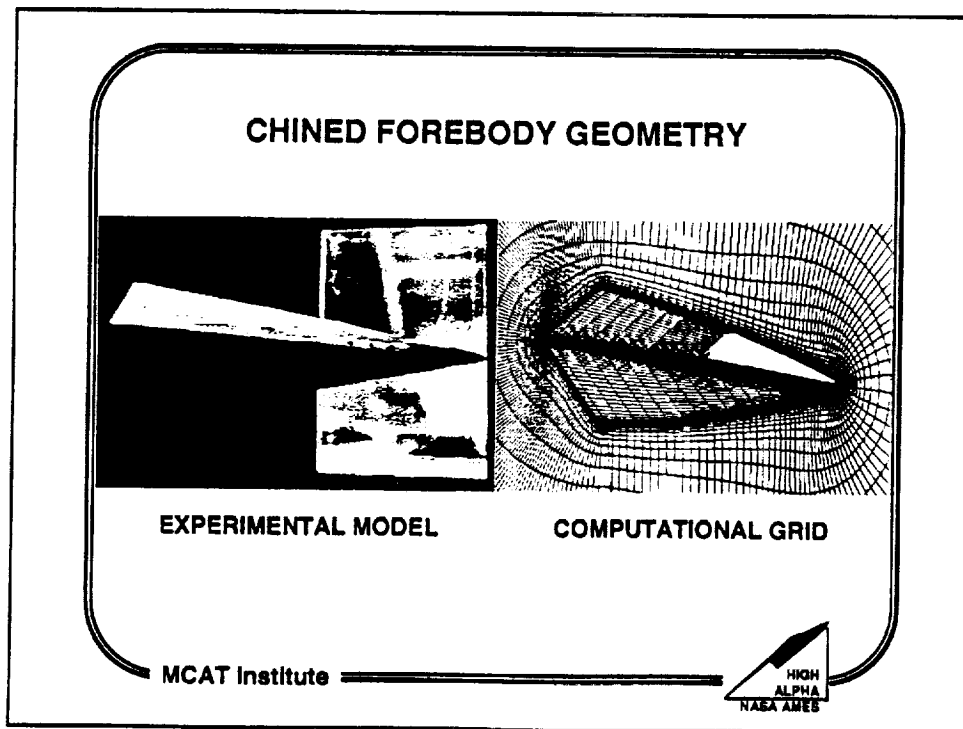
The effect that tangential slot blowing has on the flow field about the HARV can be seen using off-surface instantaneous streamlines. At very low blowing rates, the jet does not have enough energy or momentum to change the position of the vortices due to the nose. Instead, the jet becomes entrained in the blowing-side vortex and separates. Since the flow field remains essentially unchanged, there is little or no yawing moment produced. At moderate blowing rates, the jet remains attached to the surface due to the Coanda effect. The jet moves the blowing-side vortex and merges with the non-blowing-side vortex. This significantly alters the flow field near the nose, as well as the interaction of the vortices due to the nose and the LEX vortices. Therefore, significant yawing moment is obtained. At very high blowing rates, overblowing occurs. In order to obtain the high jet mass flow rate, the total pressure of the jet is increased such that the jet chokes at the exit, and the jet exit pressure is almost five times the local static pressure. Consequently, the jet is underexpanded. As the jet exits the slot, it rapidly expands, causing it to separate from the surface. This early separation limits the ability of blowing to generate yawing moment, leading to the leveling off of the yawing moment with increasing mass flow ratio.



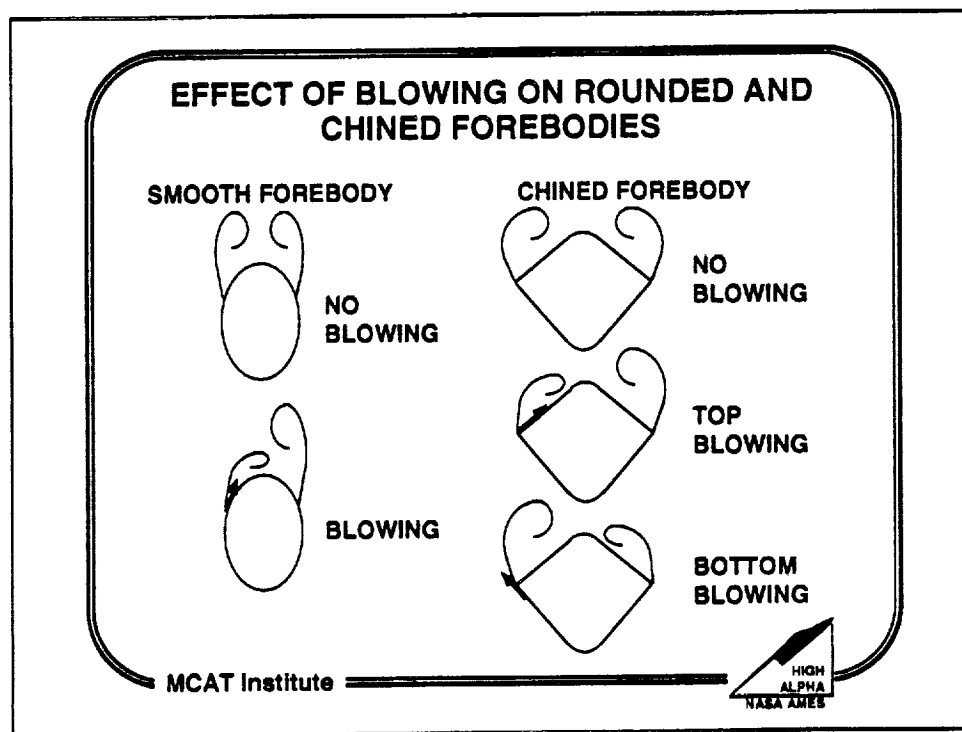
The time required for the yawing moment to fully develop from the onset of blowing must be known in order to determine the usefulness of forebody tangential slot blowing on a flight aircraft. Large force onset time lags would render the system useless. Full-scale⁵ and sub-scale⁹ wind tunnel tests have been conducted to quantify the force onset time lag associated with blowing. The results indicate time lags on the order of 0.1 second real time, or 1.0 non-dimensional time unit. Computations are obtained in a time-accurate mode using the isolated F-18 forebody to determine if the time lags can be resolved numerically and to extend the experimental data to higher freestream Mach numbers.⁸ The computed results indicate the time required to fully establish the yawing moment is approximately 1.0 non-dimensional time unit, or the time it takes for a particle to travel the length of the forebody. This result is consistent with the experimental data. The response of the surface pressure coefficient at two fuselage stations on the forebody are also presented. At F.S. 142, there is a slight delay before the pressure drops in response to the blowing. This delay is larger at F.S. 184 since the disturbance requires more time to convect downstream. However, the time lag associated with blowing are well within acceptable limits and do not present a problem in implementation of blowing on a flight vehicle.



Future aircraft designs will differ from current aircraft designs. One such difference is the use of chined forebodies in future aircraft, compared to the smooth forebodies in use today. The use of tangential slot blowing on future aircraft designs will depend on its effectiveness in conjunction with the chined forebody. To address this question, an experimental investigation was undertaken at Cal Poly, San Luis Obispo, using a model of a chined forebody in the low-speed 3 by 4 ft. wind tunnel.¹⁰ The model contained a slot located on the top surface. As in the full-scale F/A-18 model, the slot was divided into sections, with each section connected to a valve, so that the length of the active slot region can be controlled. Force and moment data were obtained using a sting balance. A numerical study was undertaken to compliment and extend the wind tunnel experiment.¹¹ A computational model of the wind tunnel model was developed, with the slot geometry modeled, using the overset grid method, hyperbolic grid generator, and grid communications software used to develop the HARV grid system.

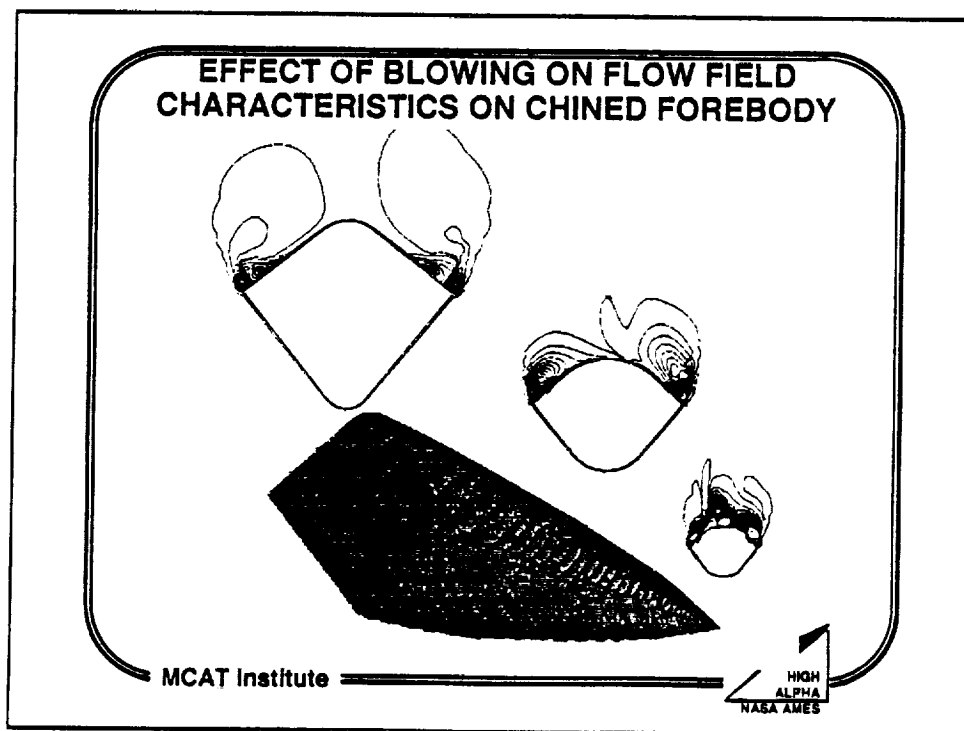


In a "conventional", smooth forebody, tangential slot blowing moves the primary crossflow separation location toward the leeward symmetry plane on the blowing side, and there may or may not be a secondary separation on the blowing side. For a chined forebody, the primary separation occurs at the chine for the no-blowing case. Unlike a "conventional", smooth forebody, blowing from a slot located on the top surface of the chined forebody does not move the primary separation line from its location at the chine line, but it does disturb the no-blowing flowfield, and draws the blowing-side vortex toward the surface while the non-blowing-side vortex moves away from the surface. Blowing outboard from a slot located on the bottom surface has a similar, but mirror-image effect. Here the jet forces the blowing-side vortex away from the body surface, while the non-blowing-side vortex moves closer to the body. In contrast to a conventional forebody, the primary crossflow separation remains located at the chine and a secondary separation does exist. These changes in the flowfield generate side forces and yawing moments which have the potential of being employed to control the aircraft at high angles of attack.

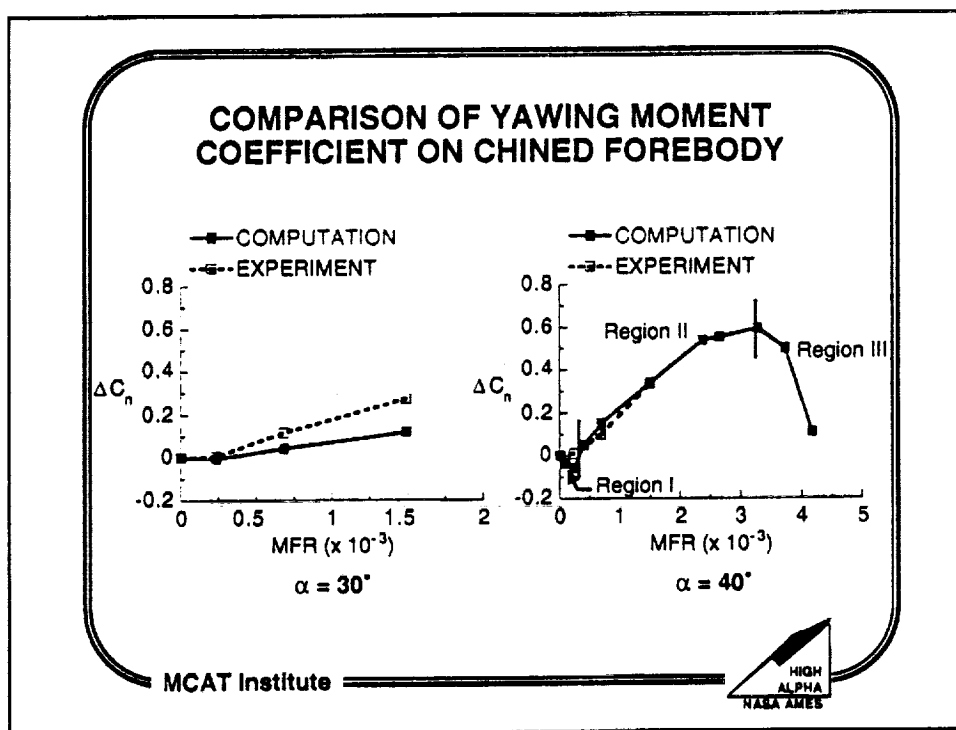


Solutions were computed for flow about the chined forebody with tangential slot blowing from the starboard side (pilot's view) of the body.¹¹ The blowing slot is one inch in length, starting 0.5 inch from the nose tip and extending aft. Here is the surface flow pattern and helicity density contours for the solution with $MFR = 1.49 \times 10^{-3}$. Primary crossflow separation lines occur at the chine line, and extend along the entire length of the body. In addition, the secondary and tertiary crossflow separation lines extend from the nose of the forebody to the end of the forebody. Further, a fourth crossflow separation line appears near the back of the forebody. The surface flow pattern shows that the largest changes in the flowfield occur in the blowing region near the nose. The separation lines aft of the blowing region do not appear to greatly change positions.

The helicity density contours are shown in crossflow planes at three axial stations on the forebody. The helicity density contours grow larger and more diffuse in the axial direction. The first axial station is located in the middle of the blowing region. It shows that the primary vortex on the blowing side is entrained by the jet and moves downward towards the surface due to the Coanda effect. The non-blowing-side vortex moves away from the surface. Here the movement of the vortices, and the resulting lower pressure region on the blowing side cause a side force and yawing moment toward the blowing-side. The helicity density contours at the other two axial stations show that the blowing-side vortices move closer to the surface and the non-blowing-side vortices move away from the surface when compared to the no-blowing solution which causes tangential slot blowing to be effective in this region.

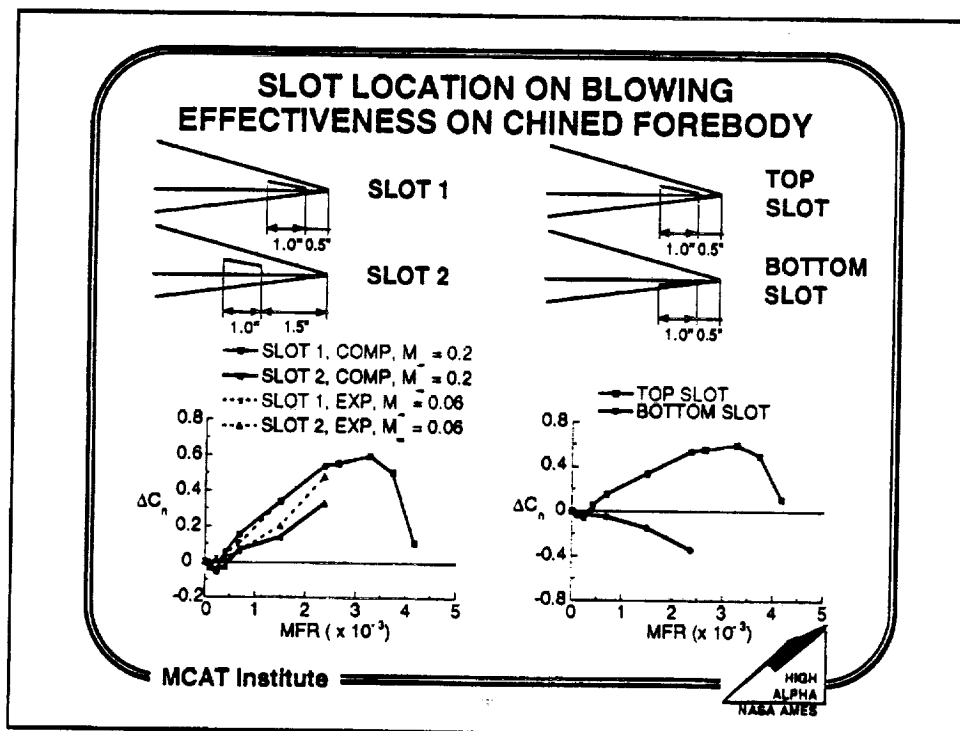


For $\alpha = 30^\circ$, both the experimental and computational results show that the incremental yawing moment increases smoothly as the mass flow ratio increases. The computational results underpredict the experimentally-measured yawing moment. At $\alpha = 40^\circ$, however, the computed results show three distinct regions of effectiveness. In the first region, low blowing rates produce a negative ΔC_n . This is caused by the low-energy jet moving the primary blowing-side vortex away from the surface. This results in a higher pressure region on the blowing side which causes the negative yawing moment. In Region II, this trend reverses, and ΔC_n increases with increasing MFR until a maximum is reached. The jet remains attached to the surface due to the Coanda effect, resulting in the positive yawing moment. In Region III, further increases in MFR causes a reduction in ΔC_n . At the higher mass flow ratios, the pressure at the jet exit is greater than the freestream pressure. The jet rapidly expands after leaving the blowing slot, causing the jet to separate, pushing the primary vortex away from the surface. Similar trends have been observed in experiments using the F/A-18 with jet and slot blowing.⁹ At the higher angle of attack, the computed results are generally in better agreement with the experiment, except at the low MFR values.



Experimentally, it was found that the most effective slot configuration of those tested on the generic chined forebody was a slot one inch long located 0.5 inches from the tip of the nose (referred to as Slot 1) and blowing tangentially toward the leeward symmetry plane. To investigate the effect of axial slot location computationally, solutions were obtained for an additional slot configuration (Slot 2), which had the same one inch length as Slot 1, but extended rearward from a point 1.5 inches from the tip of the nose. The variation of ΔC_n with MFR for the two slot configurations is similar. The computed results for both slot configurations show a force reversal at low MFRs, followed by increasing ΔC_n with increasing MFR. Slot 1 produces a larger magnitude of ΔC_n for a given MFR than does Slot 2. This trend is clearly seen at the higher MFRs, and was seen in both the numerical and experimental results. It is also consistent with results obtained by Degani and Schiff,¹² who found that small disturbances near the tip of the nose produce greater effects on the flowfield than disturbances placed further aft.

In order to determine whether an alternative circumferential slot location could be more effective in developing side forces and yawing moments on the body, computations were carried out for a slot located on the lower chine surface and blowing tangentially outboard. This slot had the same axial location and extent of Slot 1. For the configurations investigated, it was found that blowing from the bottom slot produces a side force and yawing moment directed away from the blowing side. It was determined that blowing from the upper slot produces a greater change in yawing moment for a given MFR than does blowing from the bottom slot.

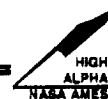


Forebody tangential slot blowing has been shown to be viable method of generating forces and moments on an aircraft flying at high angle of attack. Computational fluid dynamics is used to analyze forebody blowing about the F/A-18 aircraft geometry. The results obtained from this analysis compliments the data generated by sub-scale and full-scale wind tunnel tests. Comparison of computed results with experimental data show good comparison in such areas as surface pressure coefficient. The detailed flow picture obtained from computational solutions show the asymmetric LEX vortex burst caused by blowing, as well as the changes in the frequency of the aerodynamic loads impinging on the vertical tails. Computed results also show that blowing can be effective over a range of freestream Mach numbers and blowing rates. High blowing rates, however, can lead to overblowing, where a leveling off or reduction in yawing moment occurs.

CONCLUSIONS

- **CFD ANALYSIS HAS SHOWN THAT TANGENTIAL SLOT BLOWING ON THE HARV**
 - CAUSES ASYMMETRIC LEX VORTEX BURST
 - ALTERS THE FREQUENCY OF THE TAIL BUFFET LOADS
 - REMAINS EFFECTIVE OVER A RANGE OF FREESTREAM MACH NUMBERS AND MASS FLOW RATIOS
 - FORCE ONSET TIME LAG IS SMALL
- **COMPARISON WITH EXPERIMENTAL DATA IS GOOD**
 - SURFACE PRESSURE COEFFICIENT
 - YAWING MOMENT COEFFICIENT
 - FORCE ONSET TIME LAG

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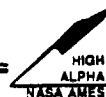


The computational investigation shows that forebody tangential slot blowing can generate significant side force and yawing moment on a generic chined forebody. The computed yawing moment compares well with the available experimental data, although slight discrepancies do exist, especially at the lower angle of attack. At the higher angle of attack, force reversal and the effects of overblowing are observed computationally. Force reversal occurs when the jet pushing the blowing-side vortex away from the surface, instead of entraining it closer to the surface, which happens at higher blowing rates. In the case of the chined forebody, overblowing causes a significant reduction in the yawing moment, instead of the leveling off observed in the F-18 isolated forebody computations. The flow mechanisms involved are the same, however, with the jet being underexpanded at the slot exit, which causes a rapid expansion and separation of the jet from the surface. Slot location also has a role in the effectiveness of blowing. A slot located further forward generated more yawing moment, as observed in the experiment. A slot located on the top surface is more effective than a slot located on the bottom surface. The computational analysis serves as a means of enhancing and extending the information obtained from experiments. Using both in conjunction, a more complete understanding of forebody tangential slot blowing is obtained.

CONCLUSIONS (CONTINUED)

- **TANGENTIAL SLOT BLOWING IS EFFECTIVE ON A GENERIC CHINED FOREBODY**
- **COMPUTED RESULTS COMPARE WELL WITH EXPERIMENTAL DATA**
- **FORCE REVERSAL AND OVERBLOWING ARE OBSERVED IN THE COMPUTED RESULTS**
- **SLOT LOCATION HAS EFFECT ON YAWING MOMENT GENERATED**
 - **FORWARD SLOT MORE EFFECTIVE THAN AFT SLOT**
 - **TOP SLOT MORE EFFECTIVE THAN BOTTOM SLOT**

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